CHAPTER 6

STATIC ANALYSIS

6-1. Introduction. This chapter describes static analysis of concrete arch dams using the FEM. The purpose of FEM analysis is to perform more accurate and realistic analysis by eliminating many assumptions made in the traditional methods. The main advantages of FEM are its versatility and its ability for exploring foundation conditions and representing the more realistic interaction of dam and foundation rock. In particular, nonhomogeneous rock properties, weak zones, clay or gouge seams, and discontinuities in the foundation may be considered in the analysis to evaluate their effects on the stress distribution. The cracked sections or open joints in the structure can be modeled; thrust blocks and the spillway openings in the crest are appropriately included in the mathematical models; and the stresses around the galleries and other openings can be investigated.

6-2. Design Data Required. Design data needed for structural analysis of a concrete arch dam are: Poisson's ratio, strength and elastic properties of the concrete, Poisson's ratio and deformation modulus of the foundation rock, unit weight and coefficient of thermal expansion of the concrete, geometric data of the dam layout, geometric data of spillway openings and thrust blocks, operating reservoir and tailwater surfaces, temperature changes within the dam, probable sediment depth in the reservoir, probable ice load, and the uplift pressure. A description of each data type is as follows:

a. Concrete Properties. The material properties of the concrete for use in static analysis are influenced by mix proportions, cement, aggregate, admixtures, and age. These data are not available beforehand and should be estimated based on published data and according to experience in similar design and personal judgment; however, actual measured data should be used in the final analysis as they become available. The concrete data needed for the analysis are:

(1) Sustained modulus of elasticity

(2) Poisson's ratio

(3) Unit weight

(4) Compressive strength

(5) Tensile strength

(6) Coefficient of thermal expansion

The sustained modulus of elasticity is used in the analyses of the static loads to account for the creep effects. In the absence of long-term test data, a sustained modulus of elasticity equal to 60 to 70 percent of the instantaneous modulus may be used. The standard test method for measurement of the concrete properties is given in Chapter 9.

b. Foundation Properties. The foundation data required for structural analysis are Poisson’s ratio and the deformation modulus of the rock supporting the arch dam. Deformation modulus is defined as the ratio of applied stress to resulting elastic plus inelastic strains and thus includes the effects of joints, shears, and faults. Deformation modulus is obtained by in situ tests (Structural Properties, Chapter 9) or is estimated from elastic modulus of the rock using a reduction factor (Von Thun and Tarbox 1971 (Oct)). If more than one material type is present in the foundation, an effective deformation modulus should be used instead. For nonhomogeneous foundations, several effective deformation modulus values may be needed to adequately define the foundation characteristics.

c. Geometric Data. The necessary data for constructing a finite element mesh of an arch dam is obtained from drawings containing information defining the geometry of the dam shape. These include the plan view and section along the reference plane, as shown in Figures 1-5 and 1-6. In practice, arch dams are geometrically described as multicentered arches with their centers varied by elevation in addition to the arch opening angles and radii varying for each side with elevation. Elliptical arch shapes may be approximated for the various elevations by three-centered arches including central segments with shorter radii and two outer segments with equal but longer radii. The basic geometric data of a multicentered dam at each elevation for the upstream and downstream faces are as follows:

(1) Radius of central arcs

(2) Radius of outer arcs

(3) Angles to point of compounding curvatures

(4) Angles to abutments

(5) Location of centers of central arcs

Preparation of finite element mesh data from these geometric data is very time consuming because most general-purpose finite element programs cannot directly handle these data or the similar ADSAS input data; however, GDAP (Ghanaat 1993a), a specialized arch dam analysis program, can automatically generate coordinates of all nodal points, element data, element distributed loads, and the nodal boundary conditions from such limited geometric data or even directly from ADSAS input data for any arch dam-foundation system. Geometric data for modeling thrust blocks, spillway openings, and other structural features are obtained directly from the associated design drawings.

d. Static Loads. The basic loads contributing to the design or safety analysis of arch dams are gravity, reservoir water, temperature changes, silt, ice, uplift, and earthquake loads. The data needed to specify each individual static load are described in this section. Earthquake loads and their effects are discussed in Chapter 7, and the various load combinations are presented in Chapter 4.

(1) Gravity Loads. Gravity loads due to weight of the material are computed from the unit weight and geometry of the finite elements. The dead weight may be applied either to free-standing cantilevers without arch action

to simulate the construction process or to the monolithic arch structure with all the contraction joints grouted. Although the first assumption usually is more appropriate, a combination of the two is more realistic in situations where the vertical curvature of the cantilevers is so pronounced that it is necessary to limit the height of free-standing cantilevers by grouting the lower part of the dam. In those cases, a gravity load analysis which closely follows the construction sequence is more representative. The weight of the appurtenant structures that are not modeled as part of the finite element model but are supported by the dam, if significant, are input as external concentrated loads and are applied to the supporting nodal points.

(2) Reservoir Water. Most finite element programs such as the GDAP and SAP-IV handle hydrostatic loads as distributed surface loads. The surface loads are then applied to the structure as concentrated nodal loads. Therefore, hydrostatically varying surface pressure can be specified by using a reference fluid surface and a fluid weight density as input.

(3) Temperature. Temperature data needed in structural analysis result from the differences between the closure temperature and concrete temperature expected in the dam during its operation. Temperature changes include high and low temperature conditions and usually vary: by elevation, across the arch, and in the upstream-downstream direction. Temperature distribution in the concrete is determined by temperature studies (Chapter 8) considering the effects of transient air and water temperatures, fluctuation of reservoir level, and the solar radiation. The nonlinear temperature distribution calculated in these studies is approximated by straight line distribution through the dam thickness for the use in structural analysis performed in using shell elements. However, if several solid elements are used through the thickness, a nonlinear temperature distribution can be approximated.

(4) Silt. Arch dams often are subjected to silt pressures due to sedimentary materials deposited in the reservoir. The saturated silt loads are treated as hydrostatically varying pressures acting on the upstream face of the dam and on the valley floor. A silt reference level and the weight density of the equivalent fluid are needed to specify the silt pressures.

(5) Ice. Ice pressure can exert a significant load on dams located at high altitudes and should be considered as a design load when the ice cover is relatively thick. The actual ice pressure is very difficult to estimate because it depends on a number of parameters that are not easily available. In that case, an estimate of ice pressure as given in Chapter 4 may be used.

(6) Uplift. The effects of uplift pressures on stress distribution in thin arch dams are negligible and, thus, may be ignored; however, uplift can have a significant influence on the stability of a thick gravity-arch dam and should be considered in the analysis. For more discussion on the subject, refer to "Theoretical Manual for Analysis of Arch Dams" (Ghanaat 1993b).

6-3. Method of Analysis. The static analysis of an arch dam should be based on the 3-D FEM. The FEM is capable of representing the actual 3-D behavior of an arch dam-foundation system and can handle any arbitrary geometry of the dam and valley shape. Furthermore, the method can account for a variety of loads and is equally applicable to gravity arch sections as well as to slender and doubly curved arch dam structures.

a. The FEM is essentially a procedure by which a continuum such as an arch dam structure is approximated by an assemblage of discrete elements interconnected only at a finite number of nodal points having a finite number of unknowns. Although various formulations of the FEM exist today, only the displacement-based formulation which is the basis for almost all major practical structural analysis programs is described briefly here. The displacement-based FEM is an extension of the displacement method that was used extensively for the analysis of the framed and truss type structures before the FEM was developed (Przemieniecki 1968). Detailed formulations of the FEM are given by Zienkiewicz (1971), Cook (1981), and Bathe and Wilson (1976). Application of the method to the analysis of arch dams is presented in the "Theoretical Manual for Analysis of Arch Dams" (Ghanaat 1993b). Following is an outline of the finite element computer analysis for static loads, as a sequence of analytical steps:

(1) Divide the dam structure and the foundation rock into an appropriate number of discrete subregions (finite elements) connected at joints called nodal points. For a discussion of mesh density, see paragraph 6-4.

(2) Compute the stiffness matrix of each individual element according to the nodal degrees of freedom and the force-displacement relationships defining the element.

(3) Add the stiffness matrices of the individual elements to form the stiffness matrix of the complete structure (direct stiffness method).

(4) Define appropriate boundary conditions and establish equilibrium conditions at the nodal points. The resulting system of equations for the assembled structure may be expressed as:

$$ku = p \tag{6-1}$$

where

k = stiffness matrix
u = displacement vector
p = load vector

(5) Solve the system of equations for the unknown nodal displacements u.

(6) Calculate element stresses from the relationship between the element strains and the nodal displacements assuming an elastic strain-stress relationship.

b. Most general-purpose finite element computer programs follow these above analytical steps for static structural analysis, but their applicability to arch dams may be judged by whether they have the following characteristics:

(1) An efficient graphics-based preprocessor with automatic mesh generation capabilities to facilitate development of mathematical models and to check the accuracy of input data.

(2) Efficient and appropriate finite element types for realistic representation of the various components of the dam structure.

(3) Efficient programming methods and numerical techniques appropriate for the solution of large systems with many degrees of freedom.

(4) Postprocessing capabilities providing graphics for evaluation and presentation of the results.

c. SAP-IV (Bathe, Wilson, and Peterson 1974) and GDAP (Ghanaat 1993a) are two widely used programs for the analysis of arch dams. These programs are briefly described here. SAP-IV is a general-purpose finite element computer program for the static and dynamic analysis of linearly elastic structures and continua. This program has been designed for the analysis of large structural systems. Its element library for dam analysis includes eight-node and variable-number-node, 3-D solid elements. The program can handle various static loads including hydrostatic pressures, temperature, gravity due to weight of the material, and concentrated loads applied at the nodal points. However, the program lacks pre- and postprocessing capabilities. Thus, finite element meshes of the dam and foundation must be constructed manually from the input nodal coordinates and element connectivities. Also, the computed stress results are given in the direction of local or global axes and cannot be interpreted reliably unless they are transformed into dam surface arch and cantilever stresses by the user.

d. GDAP has been specifically designed for the analysis of arch dams. It uses the basic program organization and numerical techniques of SAP-IV but has pre- and postprocessing capabilities in addition to the special shell elements. The thick-shell element of GDAP, which is represented by its mid-surface nodes, uses a special integration scheme that improves bending behavior of the element by reducing erroneous shear energy. The 16-node shell is the other GDAP special dam analysis element; this retains all 16-surface nodes and uses incompatible modes to improve the bending behavior of the element. In addition to the shell elements, eight-node solid elements are also provided for modeling the foundation rock. The preprocessor of GDAP automatically generates finite element meshes for any arbitrary geometry of the dam and the valley shape, and it produces various 3-D and 2-D graphics for examining the accuracy of mathematical models. The postprocessor of GDAP displays nodal displacements and provides contours of the dam face arch and cantilever stresses as well as vector plots of the principal stresses acting in the faces.

e. Other general-purpose FEM programs, such as ABAQUS (Hibbitt, Karlsson, and Sorenson 1988), GTSTRUDL (Georgia Institute of Technology 1983), etc., can also be used in the analysis of arch dams. Special care should be used to assure that they have the characteristics identified in paragraph 6-3b. Also, the stress results from general-purpose FEM programs may be computed in local or global coordinates and, therefore, may need to be translated into surface arch and cantilever stresses by the user prior to postprocessing.

6-4. <u>Structural Modeling.</u> Arch dams are 3-D systems consisting of a concrete arch supported by flexible foundation rock and impounding a reservoir of water. One of the most important requirements in arch dam analysis is to develop accurate models representative of the actual 3-D behavior of the system. A typical finite element idealization of a concrete arch dam and its foundation rock is shown in Figure 6-1. This section presents general guidelines on structural modeling for linear-elastic static analysis of single arch dams. The guidelines aim to provide a reasonable compromise between the accuracy of the analysis and the computational costs. They are primarily based on the results of numerous case studies and not on any rigorous mathematical derivation. The procedures and guidelines for developing mathematical models of various components of an arch dam are as follows:

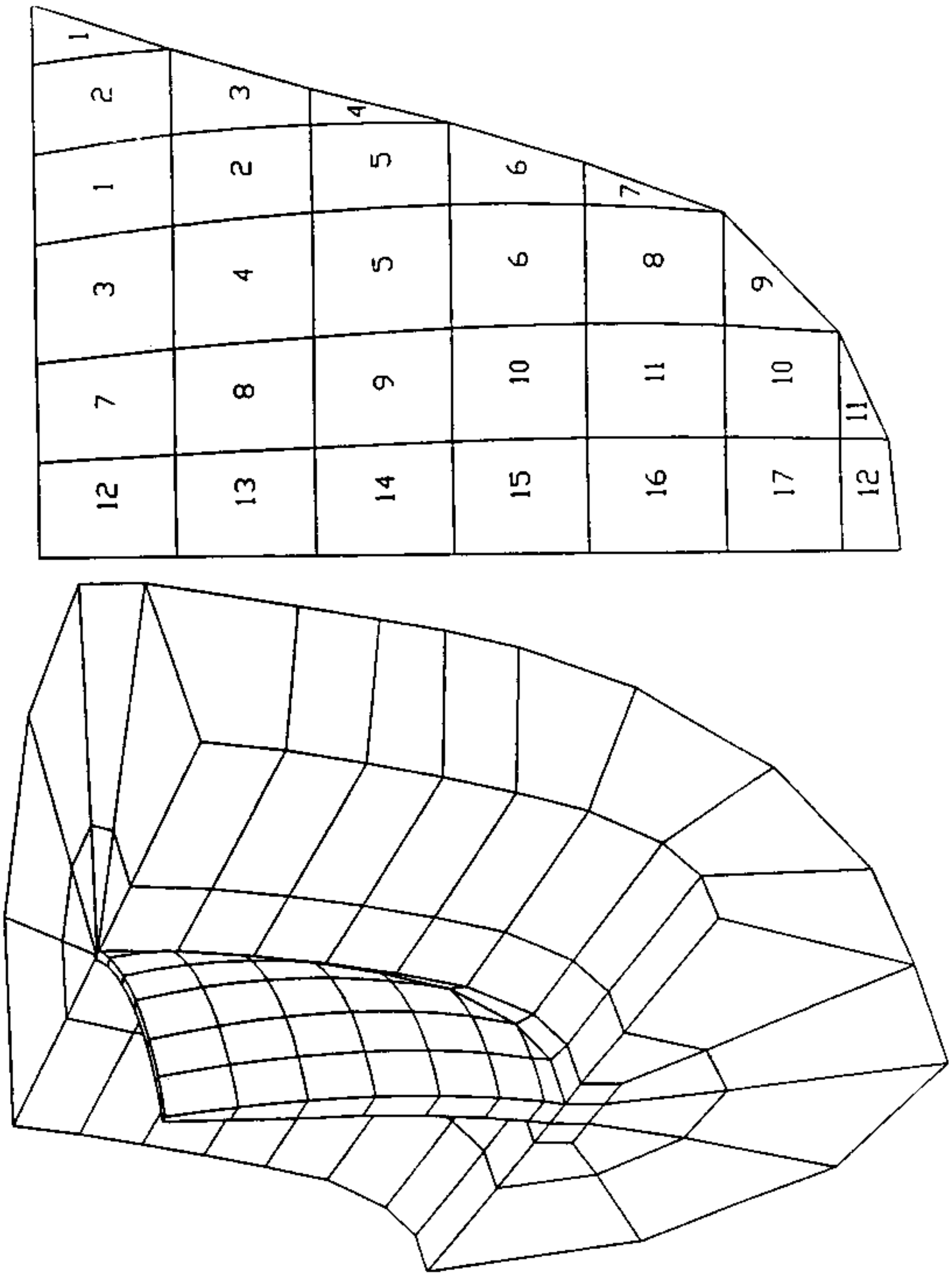
a. Dam Model. An appropriate finite element mesh for an arch dam can only be achieved by careful consideration of the dam geometry and the type of analysis for which the dam is modeled. For example, the finite element model of a double-curvature thin-shell structure differs from the model of a thick gravity-arch section. Furthermore, a structural model developed solely for a linear-elastic analysis generally is not appropriate for a nonlinear analysis.

(1) Number of Element Layers. Arch dam types may be divided, according to the geometry of their cross sections, into thin, moderately thin, and thick gravity-arch sections. Table 6-1 identifies each of these types with regard to crest thickness (t_c) and base thickness (t_b), each expressed as a ratio to the height (H). Also shown is the ratio of base-to-crest thickness. Each of these dam types may be subject to further classification based on the geometry of arch sections as described in Chapter 1. The GDAP element library contains several elements for modeling the dam and foundation, as described previously and shown in Figures 6-2, 6-3, and 6-4. The body of a thin arch dam, usually curved both in plan and elevation, is best represented by a combination of special-purpose shell elements available in the GDAP program (Figures 6-2b, 6-4c and d). The general 3-D solid element shown in Figure 6-4b, which may have from 8 to 21 nodes, can also be used, but these are not as accurate as the GDAP shell elements in representing bending moments and shear deformations of thin shell structures. In either case, a single layer of solid elements which use quadratic displacement and geometry interpolation functions in the dam face directions and linear interpolation in the dam thickness direction is sufficient to accurately represent the body of the dam (Figure 6-1). These finite elements are discussed in more detail in the "Theoretical Manual for Analysis of Arch Dams" (Ghanaat 1993b).

(a) Moderately thin arch dams are modeled essentially similar to the thin arch dams, except that 3-D solid elements should be used near the base and the abutment regions where the shell behavior assumption becomes invalid due to excessive thickness of the arch.

(b) Gravity-arch dams should be modeled by two or more layers of solid elements in the thickness direction depending on their section thickness. Any of the solid elements shown in Figures 6-4a, b, or d may be used to model the dam. It is important to note that multilayer element meshes are essential to determine a detailed stress distribution across the thickness and to provide additional element nodes for specifying nonlinear temperature distributions.

(2) Size of the Dam Mesh. There are no established rules for selecting an optimum mesh size for subdividing an arch dam in the surface directions. The best approach, however, is to define and analyze several meshes of different element types and sizes and then select the one that is computationally



a. Finite element model

b. Mesh layout

Figure 6-1. Finite element model of Morrow Point Dam and foundation

TABLE 6-1

Arch Dam Types

	t_c/H	t_b/H	t_b/t_c
Thin arch	0.025-0.05	0.09-0.25	2.9-5
Moderately thin	0.025-0.05	0.25-0.4	5-10
Thick gravity-arch	0.05 -0.10	0.5 -1.0	8-15

efficient and provides reasonably accurate results. The main factors to consider in choosing the mesh include the size and geometry of the dam, type of elements to be used, type and location of spillway, foundation profile, as well as dynamic characteristics of the dam, and the number of vibration modes required in the subsequent earthquake analysis. The size of the finite elements should be selected so that the mesh accurately matches the overall geometry, the thickness, and the curvature of the dam structures. As the dam curvature increases, smaller elements are needed to represent the geometry. The element types used to model a dam affect not only the required mesh size but greatly influence the results. For example, idealization of arch dams with flat face elements requires the use of smaller elements and, thus, a larger number of them, and yet such elements can not reproduce the transverse shear deformations through the dam which may not be negligible. On the other hand, the same dam can be modeled with fewer curved thick-shell elements such as those available in GDAP and thus obtain superior bending behavior and also include the transverse shear deformations. Figure 6-2 shows an example of three finite element meshes of Morrow Point Arch Dam with rigid foundation rock. Downstream deflections of the crown cantilever due to hydrostatic loads (Figure 6-5) indicate that normal and fine meshes of shell elements provide essentially identical results, and the coarse mesh of shell elements underestimates the deflections by less than 1 percent at the crest and by less than 10 percent at lower elevations. Similar results were obtained for the stresses but are not shown here. This example indicates that the normal mesh size provides accurate results and can be used in most typical analysis. If desired, however, the coarse mesh may be used in preliminary analyses for reasons of economy. For the thick-shell elements used in this example, various parameters such as the element length along the surface (a), the ratio of the thickness to the length (t/a), and the ratio of the length to the radius of curvature ($\phi = a/R$) for the coarse and normal meshes are given in Table 6-2 as a reference. These data indicate that the GDAP shell elements with an angle of curvature less than 20 degrees and a length equal or less than 150 feet, provide sufficient accuracy for practical analysis of arch dams with simple geometry and size comparable to that of Morrow Point Dam. For other arch dams with irregular foundation profile, or with attached spillway, or when the lower-order solid elements are used, a finer mesh than that shown in Table 6-2 may be required.

b. Foundation Model. An ideal foundation model is one which extends to infinity or includes all actual geological features of the rock and extends to

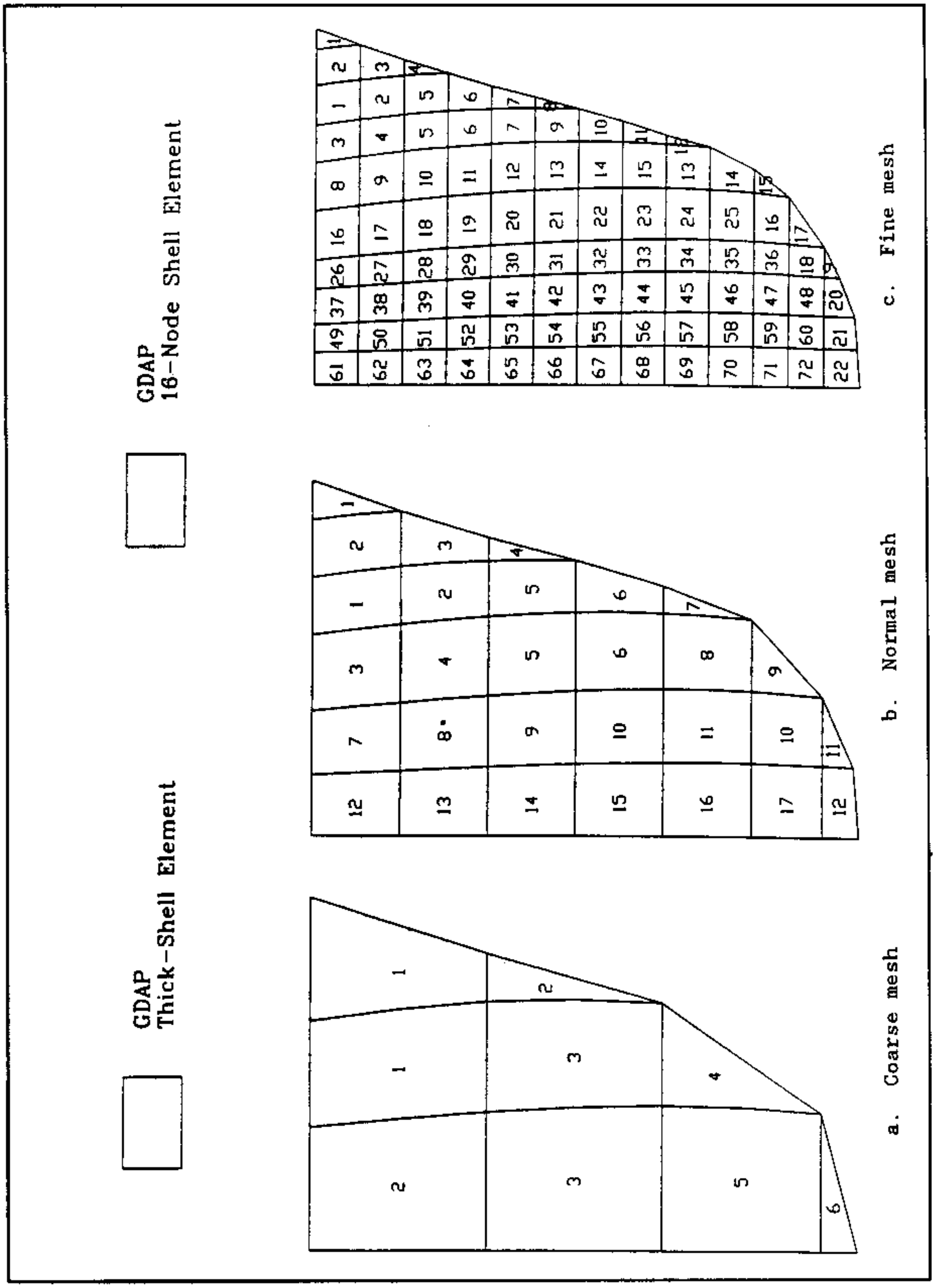


Figure 6-2. Alternative meshes for Morrow Point Dam

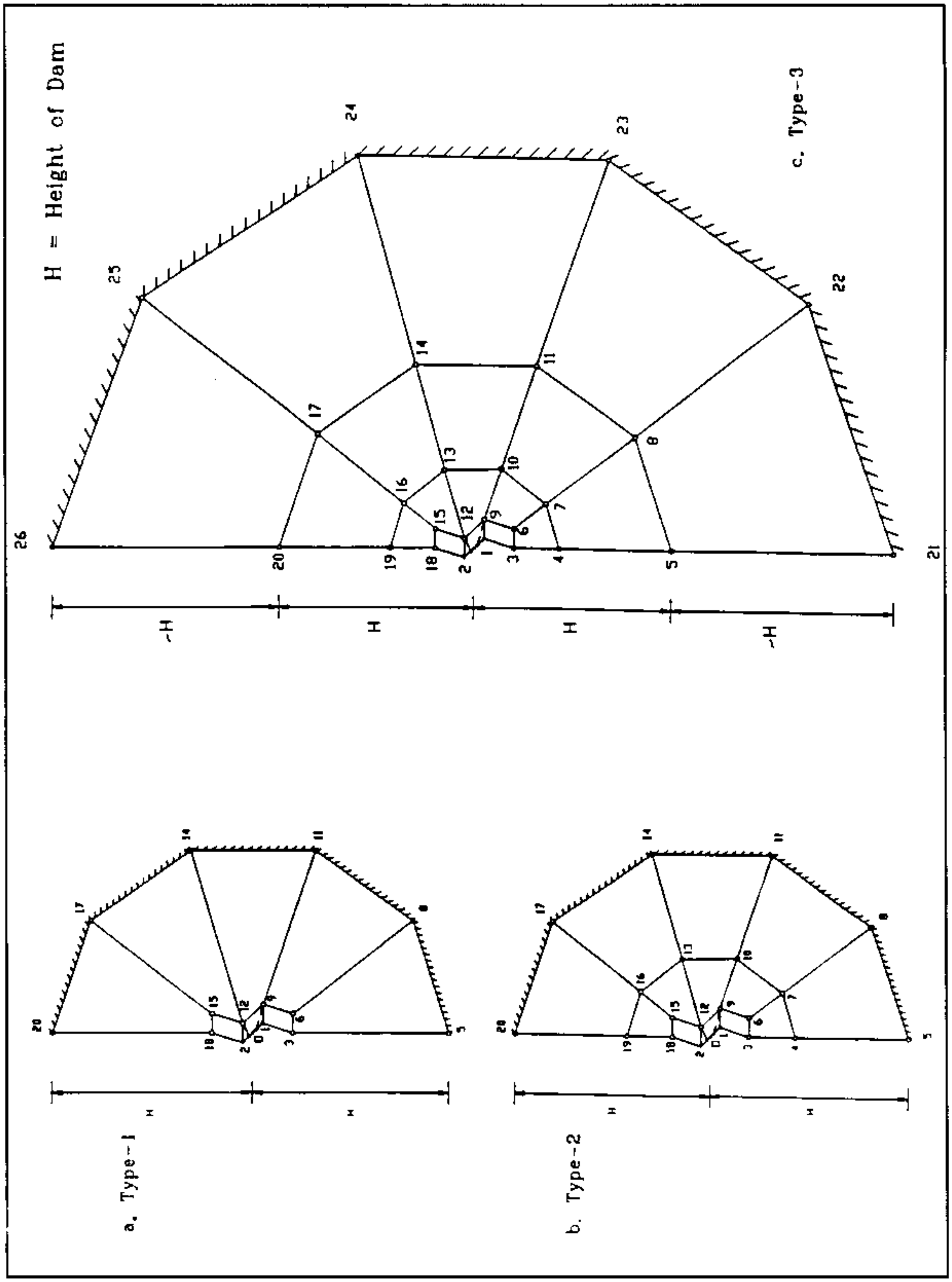


Figure 6-3. GDAP foundation mesh types

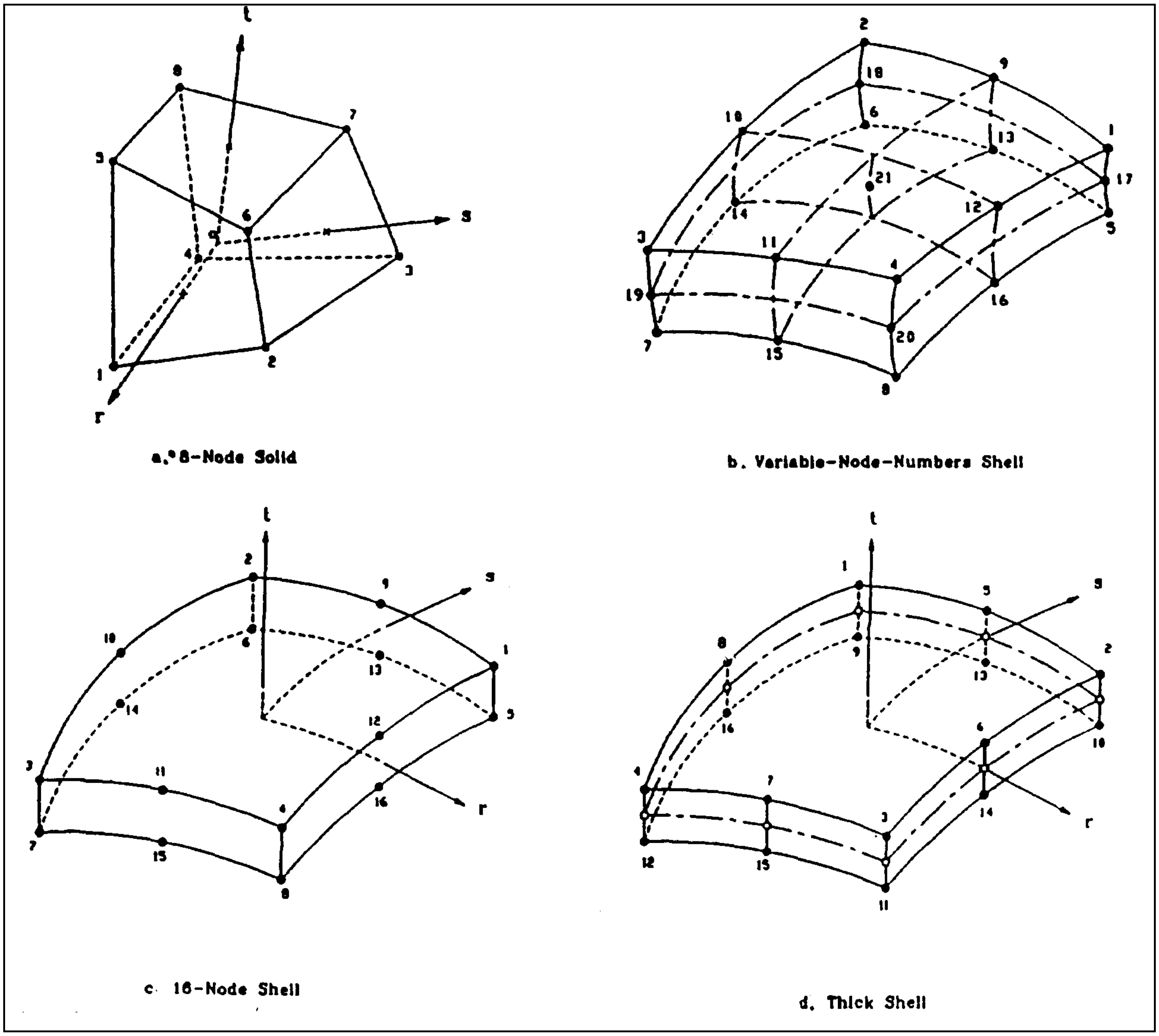


Figure 6-4. Shell and 3-D elements for arch dams

a very large distance where boundary effects on the stresses in the dam become negligible. In practice, however, these idealized models are not possible because analytical techniques to deal with infinite foundation models are not yet sufficiently developed, and very extensive models are computationally prohibitive, even if the necessary geological data were available. Instead, a simplified foundation model is used which extends a sufficiently large distance that boundary effects are insignificant; the effects of the geological formation are partly accounted for by using modulus of deformation rather than the modulus of elasticity of the rock. In general, the geometry of the rock supporting an arch dam is completely different for different dams and cannot be represented by a single rule; however, simplified prismatic foundation models available in the GDAP program (Figure 6-1) provide adequate models that can conveniently be adapted to different conditions. The foundation mesh types available in the GDAP are shown in Figure 6-3. All three meshes are

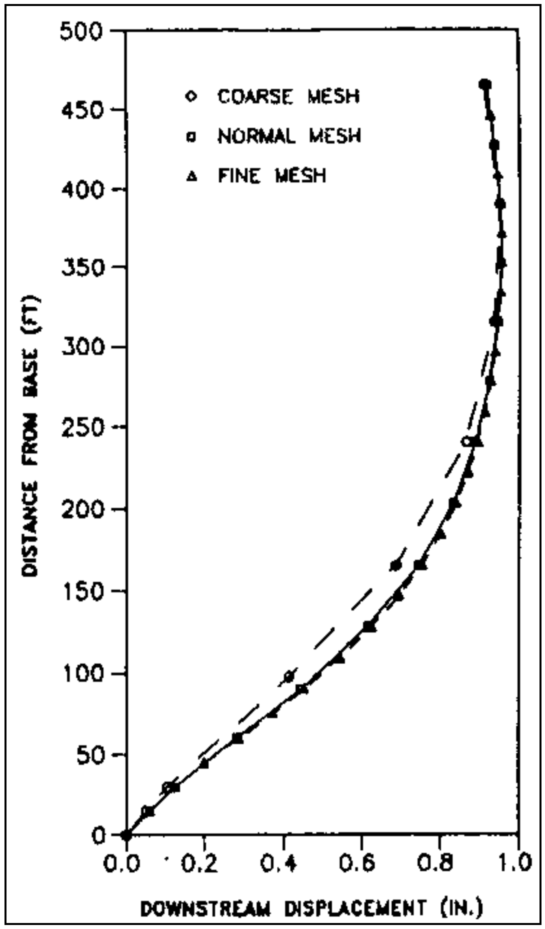


Figure 6-5. Crown section displacements of Morrow Point Dam for alternative meshes

TABLE 6-2

Element Mesh Parameters

Mesh	a ft	t/a crest	t/a base	ϕ
Coarse	150	0.08	0.34	20
Normal	75	0.15	0.70	10

constructed on semicircular planes cut into the canyon walls and oriented normal to the rock-concrete interface as indicated in Figure 6-1a; they differ only with respect to the extent of the rock and the number of elements in each semicircular plane. Eight-node solid elements with anisotropic material properties (Figure 6-4a) are most commonly used for modeling the foundation rock.

The foundation mesh is arranged so that smaller elements are located adjacent to the dam-foundation contact surface and the elements become larger toward the boundaries of the model. The size of elements used near the interface is controlled by the dam thickness, and the size of the larger elements depends on the extent of foundation mesh and the number of elements to be used in each section.

(1) Effects of Foundation Deformability. The importance of foundation interaction on the displacements and stresses resulting from loading an arch dam has long been recognized. The results of a parametric study of Morrow Point Dam, presented in Figures 6-6 through 6-8, demonstrate qualitatively the relative importance of the foundation modulus on the dam response. Three values of the rock modulus were considered: (a) rigid, (b) the same modulus as the concrete, and (c) one-fifth (1/5) the modulus of concrete. The analyses were made only for hydrostatic loads, and the effect of water load acting on the flexible foundation at the valley floor and on the flanks was also investigated. Figure 6-6 shows the deformation patterns while Figure 6-8 compares the arch and cantilever stresses along the crown cantilever section. Deformations clearly are strongly affected by the rock modulus. The rotation of foundation rock, caused by the reservoir water, results in a slight rotation of the dam section in the upstream direction which is more pronounced for weaker rocks. Stresses also are considerably affected by foundation flexibility as compared with the rigid foundation assumption and are further increased by the weight of the impounded water which causes deformations of the foundation rock at the valley floor and flanks. It is important to realize that actual foundations are seldom uniform and may have extensive weak zones. In such cases different values of rock modulus should be assigned to different zones so that the variability effects may be assessed.

(2) Size of the Foundation-Rock Region. To account for the flexibility effects of the foundation rock, an appropriate volume of the foundation should be included in the dam-foundation model to be analyzed; however, the amount of flexibility that is contributed by the foundation rock in actual field conditions has not been established. Larger foundation meshes can provide greater flexibility; however, if more finite elements are used to subdivide the foundation rock, greater data preparation and computational efforts are required. Moreover, the increased flexibility also can be obtained by using a reduced foundation modulus. Therefore, the foundation idealization models presented in Figure 6-3 may be sufficient to select the minimum mesh extent (i.e., radius of semicircle R_f) which adequately represents the foundation flexibility effects. In static analysis, flexibility of foundation affects displacements and stresses induced in the dam. For practical analysis, the minimum R_f is selected as a distance beyond which increasing R_f has negligible effects on the displacements and stresses in the dam. The static displacements along the crown cantilever of Morrow Point Dam for two concrete to rock modulus ratios and for three foundation mesh types are shown in Figure 6-7. These results and the stress results (not shown here) suggest that foundation mesh type-1 is adequate for most practical analyses and especially for foundations in which the rock modulus is equal to or greater than the concrete modulus. For very flexible foundation rocks, however, mesh type-3 with an R_f equal to two dam heights should be used.

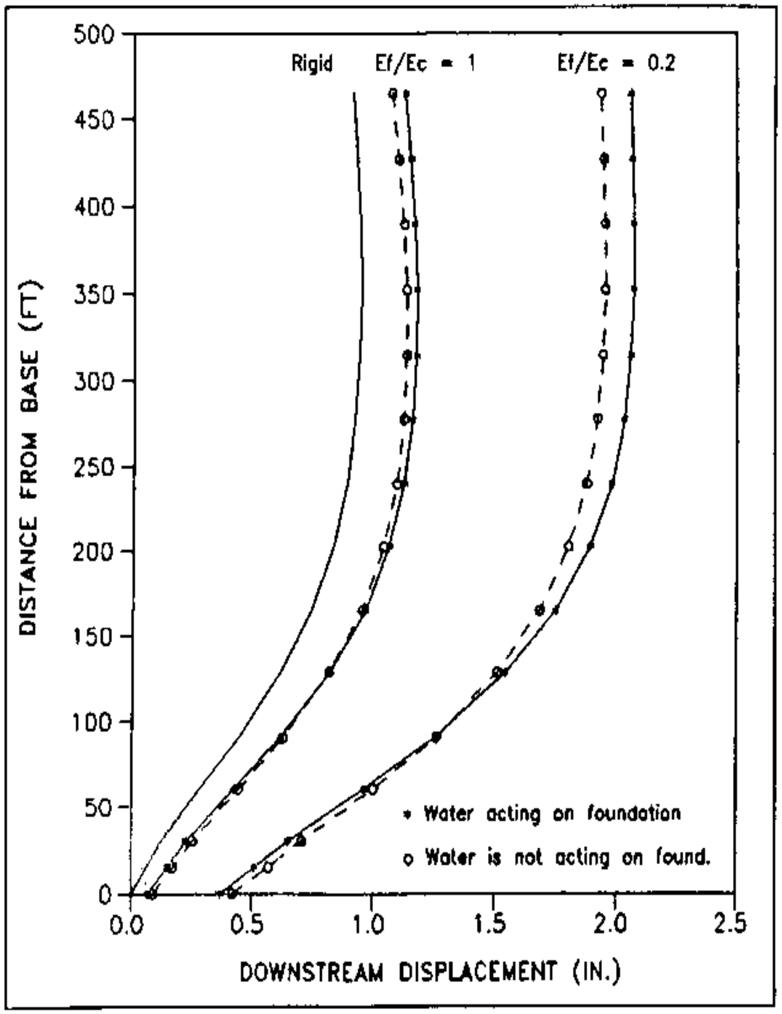


Figure 6-6. Crown section displacements of Morrow Point Dam for different foundation-to-concrete modulus ratios with and without water acting on valley floor

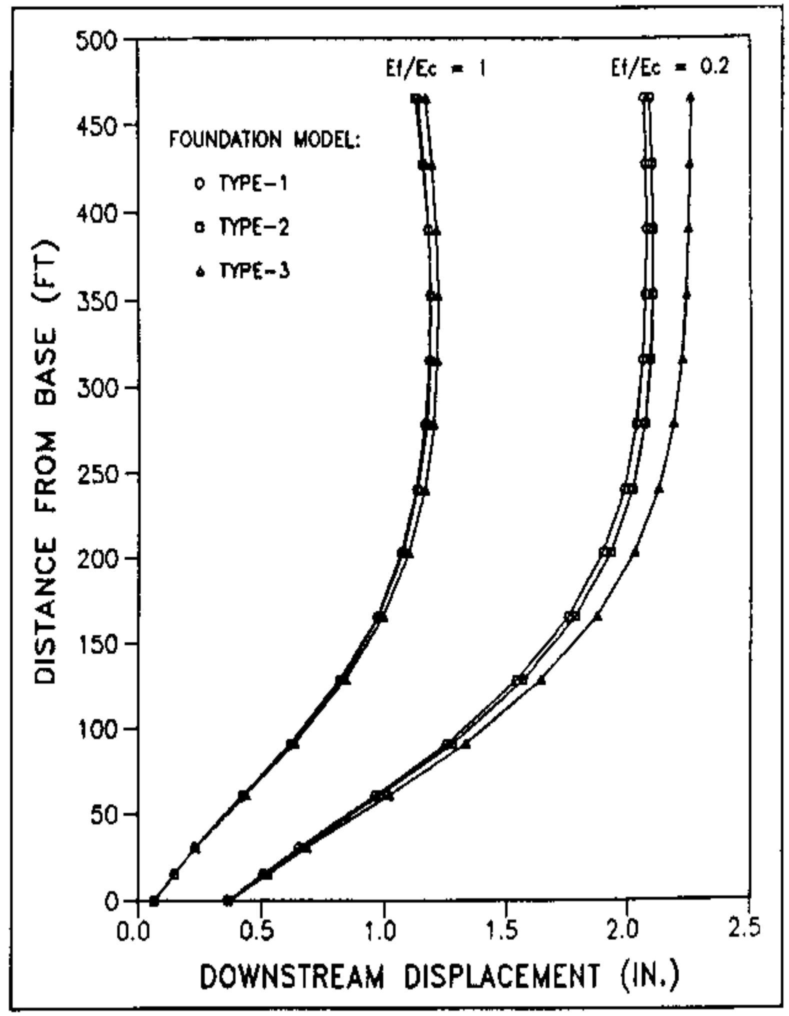


Figure 6-7. Crown section displacements of Morrow Point Dam for two foundation-to-concrete modulus ratios and for three foundation mesh types

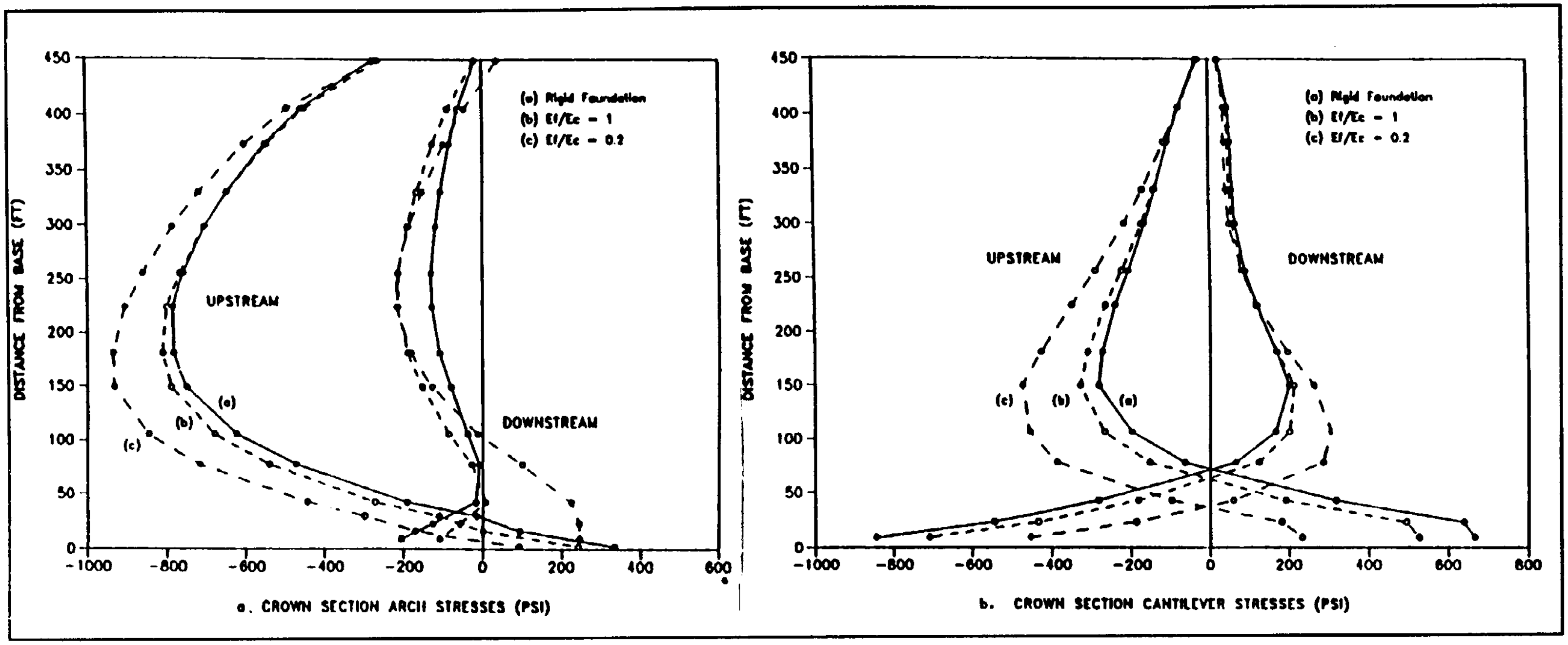


Figure 6-8. Crown section arch and cantilever stresses of Morrow Point Dam for different foundation-to-concrete modulus ratios with (c & d) and without (a & b) water loads acting on valley floor (Continued)

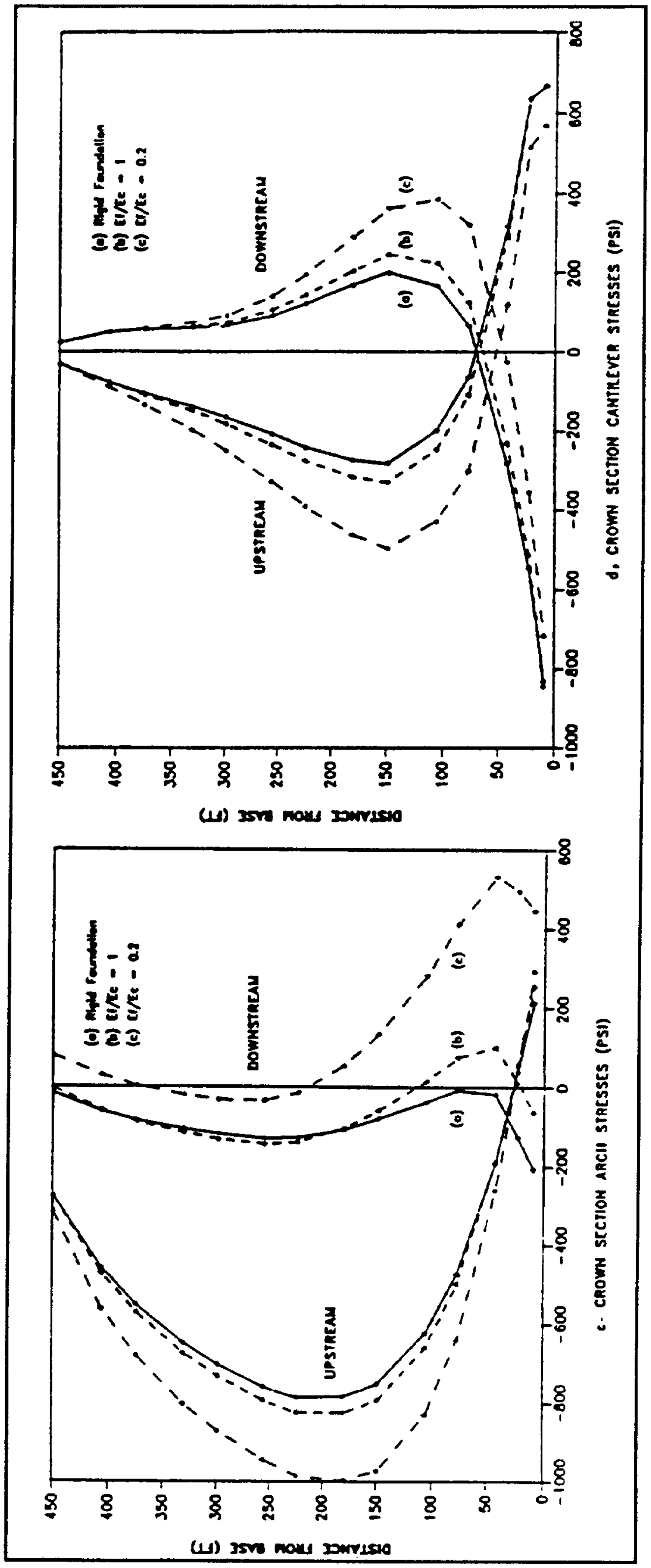


Figure 6-8. (Concluded)

c. Appurtenant Structures. All modern dams include a number of appurtenant structures and devices such as thrust blocks, spillways, galleries, and other openings. The effects of such appurtenances, if significant, should be considered in the analysis by including them in the finite element model of the dam structure.

(1) Thrust Blocks. Thrust blocks are often used as an artificial abutment where the foundation rock does not extend high enough to support the arches. Their main function is to resist the forces transmitted by the upper arches and transfer them to sound foundation rock at their base. They are a critical component of an arch dam design and should be included appropriately as part of the finite element model of the dam-foundation system. Thrust blocks may be adequately modeled using 8-node elements or any variation of 8-to-20 node solid elements shown in Figures 6-4a and 6-4b. Several element layers are usually required to match the arch mesh at the junction and to account for excessive thickness of the thrust block.

(2) Spillways, Galleries, and Other Openings. Arch dams may be designed to accommodate spillways and various other openings such as galleries, sluiceways, and river outlets. Stresses usually tend to concentrate excessively in the area of such openings, and care should be taken to reduce their effects. The large cuts made at the crests of arch dams to provide openings for overflow spillways should be included in the finite element model of the dam structure in order to assess their effects on the stress distribution. If necessary, the design of the dam should be modified to transfer load around the opening in the crest or to proportion the dam thickness to reduce the resulting stress concentrations. Spillways provided by tunnels or side channels that are independent of the arch dam are analyzed and designed separately; thus, they are not included in the finite element model of the dam.

(3) Other Openings Such as the Galleries, Sluiceways, and River Outlets. These openings introduce a local disturbance in the prevalent stress field and, in general, weaken the structure locally; however, the size of these openings usually does not have a significant influence on the overall stiffness of the dam structure, and their effect on the stress distribution may be ignored if adequate reinforcing is provided to carry the forces around the openings. Therefore, such openings need not be considered in the finite element mesh provided that the openings are small and adequately reinforced.

6-5. Presentation of Results. An important aspect of any finite element analysis is that of selecting and presenting essential information from the extensive results produced. It is extremely helpful to have the results presented in graphical form, both for checking and evaluation purposes. The results should contain information for the complete structure to make a judgement regarding the dam safety, as well as to determine whether the boundary locations are suitable or whether there are inconsistencies in the stress distribution.

a. The basic results of a typical static analysis of an arch dam consist of nodal displacements and element stresses computed at various element locations. As a minimum, nodal displacements and surface stresses for the design load combinations specified in Chapter 4 should be presented. Additional displacement and stress results due to the individual load pattern are also desirable because they provide basic information for interpretation of the indicated dam behavior.

b. Nodal displacements are computed in most computer analyses and are directly available. They are simply presented as deflected shapes across selected arches and cantilevers or for the entire dam structure in the form of 3-D plots. However, consideration should be given to whether the displacements should be indicated in global (x,y) coordinates, or in terms of radial and tangential components for each surface node. The stresses usually are computed with respect to a global coordinate system but they should be transformed to surface arch, cantilever, and principal stress directions to simplify their interpretation. The arch and cantilever stress quantities usually are plotted as stress contours on each dam face, while the principal stresses on each face are presented in the form of vector plots as shown in Figure 6-9. In addition, plots of the arch and cantilever stresses determined across the upper arch section and along the cantilever sections are desirable for further detailed study of the stresses.

6-6. Evaluation of Stress Results.

a. Evaluation of the stress results should start with careful examination of the dam response to assure the validity of the computed results. Nodal displacements and stresses due to the individual loads are the most appropriate data for this purpose. In particular, displacements and stresses across the upper arch and the crown cantilever sections are extremely helpful. Such data are inspected for any unusual distributions and magnitudes that cannot be explained by intuition and which differ significantly from the results for similar arch dams. Once the accuracy of the analytical results has been accepted, the performance of the dam for the postulated loading combinations must be evaluated.

b. This second stage of evaluation involves comparing the maximum calculated stresses with the specified strength of the concrete according to the criteria established in Chapter 11. The analysis should include the effects of all actual static loads that will act on the structure during the operations, in accordance with the "Load Combinations" criteria presented in Chapter 4. The largest compressive and tensile stress for each load combination case should be less than the compressive and tensile strength of the concrete by the factors of safety specified for each design load combination. When design criteria for all postulated loads are met and the factors of safety are in the acceptable range, the design is considered satisfactory, or, in the case of an existing dam, it is considered safe under the static loads. However, if calculated tensile stresses exceed the cracking strength of the concrete or the lift joints or if tensile stresses are indicated across the vertical monolith joints, the possibility of tension cracking and joint opening must be considered and judgement is required to interpret the results.

(1) Under the static loads, a well designed arch dam should develop essentially compressive stresses that are significantly less than the compressive strength of the concrete; however, tensile stresses may be developed under multiple loading combinations, particularly when the temperature drop is large and other conditions are unfavorable. Although unreinforced concrete can tolerate a limited amount of tensile stress, it is important to keep the

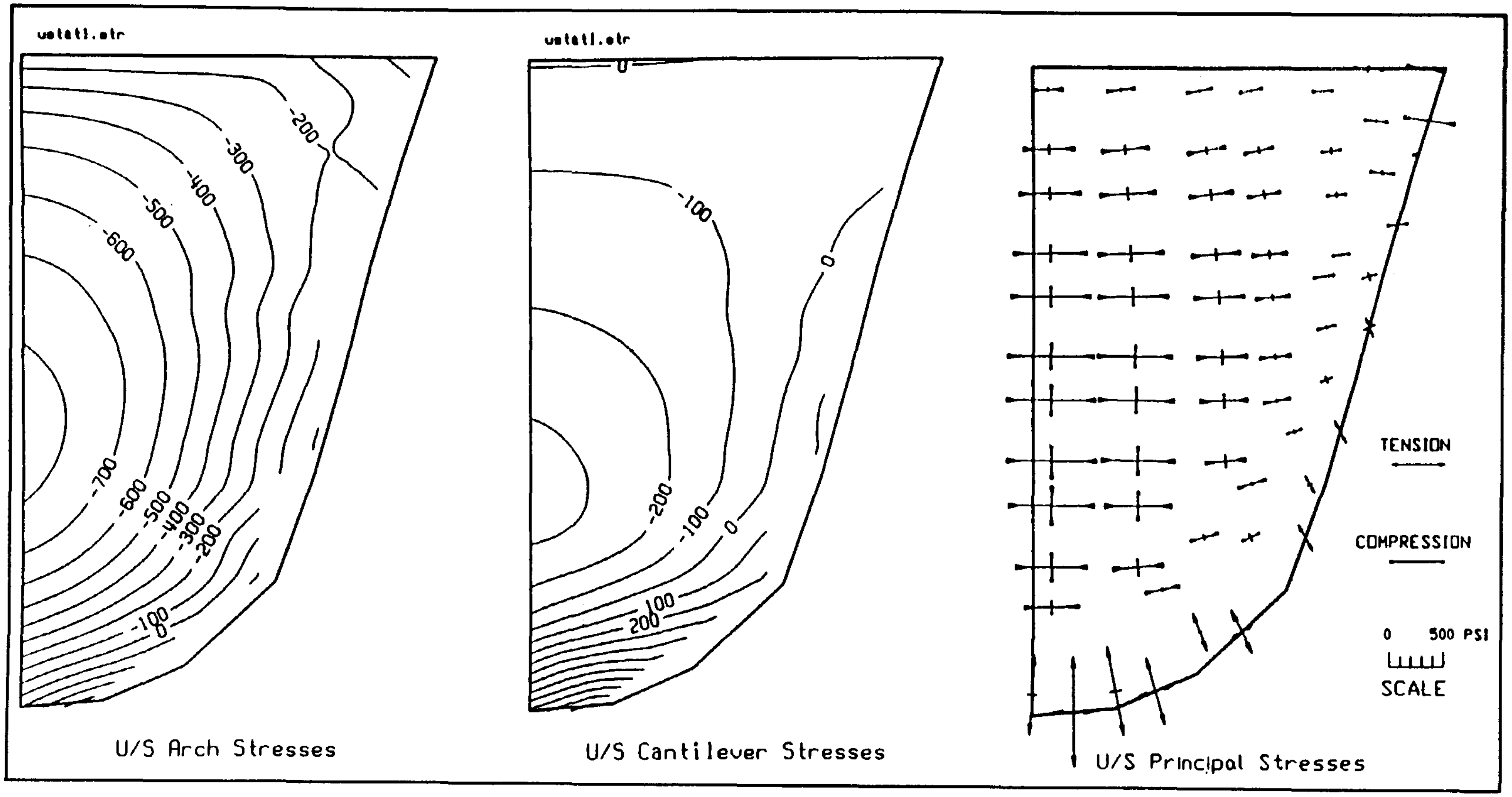


Figure 6-9. Arch and cantilever stress contours and vector plot of principal stresses for upstream face of Morrow Point Dam

tension to a minimum so that the arch has sufficient reserve strength if subjected to additional seismic loads. Vertical (cantilever) tensile stresses can be minimized by vertical arching and overhanging of the crest, but the amount by which this can be done is limited by the stress and stability of individual cantilever blocks during the construction process. When the design limits are reached or, as in the case of many existing dams, when the dam is not designed for severe loading conditions, some cracking could occur at the base and near the abutments. Linear-elastic analyses often indicate large stresses near the geometric discontinuity at the foundation contact. However, it is important to note that the tensile stresses indicated at the base of the arch dams by linear-elastic analyses are partly fictitious because these analyses do not take into account the limited bond between the concrete and foundation rock as well as the joints in the rock that could open when subjected to tensile forces. In this situation, a more realistic estimate of static stresses at the base of the dam may be obtained by a linear-elastic analysis that uses a reduced foundation deformation modulus to decrease the tension in the fractured rock.

(2) Arch dams rely significantly on arch action to transfer horizontal loads to the foundation. Therefore, in general, compressive arch stresses are expected throughout the dam; however, the analyses of monolithic arch dams with empty reservoirs, with low water levels, or with severe low temperatures have indicated that zones of horizontal tensile stresses can develop on the upstream and downstream dam faces. These tensile stresses combined with additional tensile stresses due to temperature drop tend to open the vertical contraction joints which are expected to have little or no tensile strength. It is apparent that joint opening will relieve any indicated arch tensile stresses, and the corresponding loads can be redistributed to cantilever action provided that tensile arch stresses are limited to only a small portion of the dam.

(3) Shear stresses are rarely a problem in an arch dam; nevertheless, they should be checked to make sure that they remain within the allowable limits.

c. In conclusion, the results of a linear elastic analysis are valid only if the cracking or joint openings that occur in the dam are minor and the total stiffness of the structure is not affected significantly. Therefore, it is necessary to evaluate the extent of cracking and to judge whether or not a state of no tension can safely be achieved in the dam and its foundation. If appreciable cracking is indicated, it is desirable to investigate its extent and its effects on actual stresses and deflections by analytical procedures. An approximate investigation based on a simplified nonlinear analysis may be made by eliminating the tension areas by iteration and reanalyzing the arch.